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How sprinters accelerate beyond the velocity plateau of soccer players: waveform analysis of ground reaction forces

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Abstract

Forces applied to the ground during sprinting are vital to performance. This study aimed to understand how specific aspects of ground reaction force waveforms allow some individuals to continue to accelerate beyond the velocity plateau of others. Twenty-eight male sprint specialists and 24 male soccer players performed maximal-effort 60-m sprints. A 54-force-plate system captured ground reaction forces, which were used to calculate horizontal velocity profiles. Touchdown velocities of steps were matched (8.00, 8.25 and 8.50 $m \cdot s^{-1}$) and the subsequent ground contact forces were analysed. Mean forces were compared across groups and statistical parametric mapping (*t*-tests) assessed for differences between entire force waveforms. When individuals contacted the ground with matched horizontal velocity, ground contact durations were similar. Despite this, sprinters produced higher average horizontal power (15.7-17.9 $W \cdot kg^{-1}$) than the soccer players (7.9-11.9 $W \cdot kg^{-1}$). Force waveforms did not differ in the initial braking phase (0-~20% of stance). However, sprinters attenuated eccentric force more in the late braking phase and produced a higher anteroposterior component of force across the majority of the propulsive phase, for example from 31-82% and 92-100% of stance at 8.5 $m \cdot s^{-1}$. At this velocity, resultant forces were also higher (33-83% and 86-100% of stance) and the force vector was more horizontally orientated (30-60% and 95-98% of stance) in the sprinters. These findings illustrate the mechanisms which allowed the sprinters to continue accelerating beyond the soccer players' velocity plateau. Moreover, these force production demands provide new insight regarding athletes' strength and technique training requirements to improve acceleration at high velocity.

Key words: 1D analysis, running velocity, SPM, soccer, t-test, track and field

Introduction

Accelerative sprint capacity is undoubtedly vital to success in athletics sprint events. However, it is also an essential skill in team sports. Indeed, high-speed running ability can distinguish performance levels of soccer players,[1] and straight-line sprinting frequently plays a role in decisive (goal) situations.[2] Accordingly, the ground reaction forces, which accelerate an athlete's body, during sprinting are of interest across many sports and have been extensively studied in the scientific literature.[3-10]

As horizontal running velocity increases through the acceleration phase, there is a trend for ground contact duration to decrease and flight time to increase, as shown across reconstructed 40-m accelerations.[8] At the same time, propulsive impulses decrease considerably across the acceleration phase, and although less marked, braking (negative) impulses increase.[5,7] Consequently, as acceleration progresses, lower step-to-step velocity increases are exhibited and inevitably individuals will reach a velocity at which they can no longer generate positive net impulse. This attainment of maximum velocity typically occurs 30-50 m from the starting position in sprinters.[11]

Previous studies have adopted different approaches to identify the kinetic factors which differentiate accelerative capacities and limit an individual's maximum velocity. For example, when the acceleration phase is considered as a whole (as with macroscopic approaches), it has been demonstrated that higher average anteroposterior force production across the acceleration phase and the ability to maintain a more horizontally-orientated force vector as velocity increases are crucial for performance.[8] However, when running at higher relative speeds the force vector is inevitably more vertical and a limiting factor for maximum velocity is the ability to exert high vertical force relative to body weight across short ground contacts.[9] Other studies have investigated ground reaction forces at certain distances from the block, such as in Hunter, Marshall and McNair[3] where better sprinters were found to be those who maximised propulsive impulse, but not necessarily minimised braking impulse, at the 16-m mark. This finding was more recently confirmed across entire reconstructed 40-m accelerations.[7]

The aforementioned previous studies have contributed great insight into the kinetic determinants of acceleration, which has undoubtedly advanced the field of sprint biomechanics. However, each approach naturally has both advantages and limitations. For example, by averaging kinetic variables across the acceleration phase one cannot conduct complete and detailed analysis of the performance-differentiating factors of the different parts of the acceleration phase. Whilst this can be somewhat overcome by investigating specific steps or distances from the start, such analyses could also potentially introduce biases. For example, it could be argued that different athletes progress through the acceleration phase at varying rates, and thus will have markedly different velocities and step-to-step acceleration at specific distances or steps. A study by Nagahara, Mizutani, Matsuo, et al.[5] counteracted some of these challenges by fitting polynomials to step-averaged velocities and ground reaction force variables, and extracting ground reaction force variables and acceleration values at specific relative velocities (e.g. at 75% of maximum). This novel approach demonstrated, for the first time during a single sprint, that producing large propulsive force during the whole acceleration phase, suppressing braking force when approaching maximum velocity, and producing large vertical force during the maximum velocity phase are associated with better sprint performances.[5] This apparent shift in the kinetic determinants of performance was more recently supported by step-by-step ground reaction force waveform analyses across the entire acceleration phase.[10]

However, it remains to be fully elucidated from a ground reaction force perspective why some individuals are able to continue to accelerate beyond a given velocity, whereas others are unable to and thus start to plateau towards their maximum velocity. The mechanical laws of motion dictate that those individuals who are able to continue accelerating across a step are simply those who can generate positive net impulse (taking into account the influence of air resistance). This becomes increasingly more challenging to achieve with the upright running posture and across the short contact periods associated with high velocity running, and net impulse therefore decreases as acceleration progresses.[5] However, the specific phases of force production that differentiate performance and result in higher net impulse through the suppression of braking impulse, the maximisation of propulsive impulse or both, are yet to be studied in this specific context. Thus, the aim of this study was to understand how specific aspects of ground reaction force waveforms allow some individuals to continue to accelerate beyond the velocity plateau of others.

Methods

Experimental procedures

Twenty-eight male track and field athletes (mean ± SD age, mass and height were 20 ± 1 yr, 66.5 ± 3.6 kg and 1.73 ± 0.04 m, respectively) and 24 male soccer players (20 ± 1 yr, 69.1 ± 5.7 kg and 1.73 ± 0.06 m, respectively) participated in this study. Track and field athletes were sprint specialists who had 100-m personal best times ranging from 10.88 to 11.96 s. Ethical approval for this research was granted by a local research ethics committee and all athletes provided written consent prior to participating. All trials were performed on an indoor running track. Track and field athletes performed between two and five maximal-effort 60-m sprints in spikes from their normal crouched block start position, whereas soccer players performed three maximal-effort sprints from a standing start in flat running shoes. Fifty-four force platforms (1000 Hz; TF-90100, TF-3055, TF-32120; Tec Gihan, Uji, Japan) connected to a single computer measured three-dimensional ground reaction forces during sprinting through a 52-m section from 1.5 m behind the start line to the 50.5-m mark. Some soccer players were clearly moving at the onset of certain sprints and thus, these trials were excluded from further analyses. Photocells provided 60-m time, which was used to identify each participant's fastest trial for inclusion in subsequent analyses.

Data processing

Force data were filtered and the key kinetic variables were extracted using exactly the same procedures as in Colyer, Nagahara and Salo[10]. This included an aerodynamic drag adjustment to the horizontal velocity calculation, which was verified as explained in the above paper. Figure 1 depicts the average horizontal velocity profiles of sprinters and soccer players.

Figure 1 near here

In order to compare participants' abilities to accelerate from a given velocity, horizontal velocities at the instant of touchdown were extracted and matched across individuals. However, such analyses were not deemed to be appropriate prior to the eighth step (mean distance 10.5 ± 0.8 m), as in the earlier steps, variation due to the between-group difference in starting style may be observed.[12] By the eighth step, some sprinters had already attained velocities of 7.74 ± 0.31 $m{\cdot}s^{-1}$, whereas the maximum velocities of soccer players was 8.72 ± 0.31 $m{\cdot}s^{-1}$ (9.39 ± 0.35 $m{\cdot}s^{-1}$ for sprinters). Thus, touchdown velocities of 8.00, 8.25 and 8.50 $m{\cdot}s^{-1}$ were matched (to within 0.1 $m{\cdot}s^{-1}$) across athletes, resulting in between 21 and 28 athletes in each group, as shown in Table 1. It was not deemed appropriate to analyse the steps with touchdown velocities of 7.75 and 8.75 $m{\cdot}s^{-1}$ because a limited number of athletes could be matched at those velocities (step-to-step velocity increases were large for sprinters at velocities around 7.75 $m{\cdot}s^{-1}$ and only 10 soccer players attained velocities of 8.75 $m{\cdot}s^{-1}$).

Table 1 near here

For the velocity-matched steps, braking and propulsive impulses were computed using the anteroposterior component of the ground reaction force, and ground contact durations were also calculated. Moreover, at these steps, horizontal velocities at touchdown and take-off were combined with contact duration to provide average horizontal external power, which was considered the key performance criterion for each ground contact period based on

Bezodis, Salo and Trewartha[13]. Mean forces (resultant, anteroposterior component, vertical component, and the ratio of anteroposterior component to resultant force) were calculated across these velocity-matched ground contact periods. Horizontal power and all force data were expressed relative to body mass. The flight time of the step immediately before the velocity-matched touchdown was also computed.

Statistical analyses

Standardised differences between groups in all discrete kinetic variables were calculated as the mean difference divided by the pooled standard deviation, with a smallest worthwhile effect size of ±0.2, as previously advocated.[14] Effects were deemed to be practically meaningful if they were larger than the smallest worthwhile effect size (in either direction) and the 90% confidence intervals (CI) did not overlap the opposite smallest worthwhile threshold. Open-source statistical parametric mapping (SPM) software[15] was then used to assess the parts of the force waveforms (for the ground contact period which followed the velocity-matched touchdown) that differed between athlete groups using one-dimensional two-sample *t*-tests. Force traces (resultant, anteroposterior component, vertical component and ratio of forces) were temporally normalised from 0 to 100% of stance before *t*-tests were applied to each of the 101 nodes resulting in a SPM{t} curve. Random field theory, which describes probabilistic behaviour of random curves and accounts for the smoothness of the data, was used to set a critical threshold (α = 0.05). If the SPM{t} curve exceeded this critical threshold, force was deemed to be significantly different between groups at these specific nodes. Finally, the probabilities that the observed supra-threshold regions of the SPM{t} curve with the same geometry could have resulted from repeated samplings of equally smooth random curves was computed.

Results

For clarity, the results from the 8.0 and 8.5 $m \cdot s^{-1}$ conditions will be presented here only. However, the data for the 8.25 $m \cdot s^{-1}$ condition can be found in the supporting documentation

(Table S1 and Figure S1), which provides additional information, particularly regarding the trends in the force waveforms as athletes approach their velocity plateau. Across the velocity-matched ground contacts (8.0 and 8.5 $m \cdot s^{-1}$), absolute and relative net impulses were between 42 and 73% greater for sprinters compared with soccer players (Table 2). This occurred due to the propulsive impulses being higher and braking impulses being less negative (Table 2). Moreover, across the ground contact periods following the velocity-matched touchdown, mean forces (resultant, anteroposterior component, vertical component and ratio of forces) were higher in the sprinter group compared with the soccer players (Table 3). The contact durations were similar (0.002 s difference; effect sizes were 0.28 ± 0.49 and 0.30 ± 0.45 for 8.0 and 8.5 $m \cdot s^{-1}$, respectively) between groups, yet average horizontal external power was markedly higher in the sprinters compared to soccer players (50 and 99%, respectively; Table 3). Flight times of the previous step were 0.008 s longer (effect sizes were 0.69 ± 0.45 and 0.72 ± 0.45 for 8.0 and 8.5 $m \cdot s^{-1}$, respectively) in the sprinter group compared to the soccer group (Table 3).

Table 2 near here

Table 3 near here

Resultant force produced by the sprinters was higher than that of the soccer players from 38-71% and 90-100% stance (8.0 $m \cdot s^{-1}$, Figure 2) and from 21-26%, 33-83% and 86-100% of stance (8.5 $m \cdot s^{-1}$, Figure 3). Additionally, the force vector was orientated more horizontally (higher ratio of forces) from 33-44%, 50-55% and 96-98% of stance at 8.0 $m \cdot s^{-1}$ (Figure 2) and from 30-60% and 95-98% of stance at 8.5 $m \cdot s^{-1}$ (Figure 3). A larger anteroposterior component of the ground reaction force was observed in the sprinter group, compared with the soccer group, during mid-stance (32-77% of stance at 8.0 $m \cdot s^{-1}$ and 31-82% at 8.5 $m \cdot s^{-1}$) and in the latter parts of stance (93-100% of stance at 8.0 $m \cdot s^{-1}$ and 92-100% at 8.5 $m \cdot s^{-1}$). For the stance phases with touchdown velocity of 8.0 $m \cdot s^{-1}$, vertical force was significantly higher in sprinters compared with soccer players from 39-50%, 55-62% and 88-99% of stance (Figure 2). At the higher touchdown velocity analysed in this study (8.5 m·s^{-1}) when soccer players were running very close to maximum, however, the periods of stance where these differences were exhibited were longer and the areas where the thresholds were exceeded were markedly larger than those at the lower velocities (Figure 3). For example, in the vertical direction, sprinters produced higher forces than soccer players from 22-23%, 33-77% and 86-99% of stance.

Figure 2 near here

Figure 3 near here

Discussion

This study adopted a unique approach to investigate the kinetic factors underlying accelerative performance, which allow higher maximum velocities to be achieved. By closely matching the touchdown velocities of soccer players (running at or close to maximum velocity) with those of sprinters (who were able to continue accelerating), we have identified both discrete kinetic variables and specific parts of the ground reaction force waveforms which differentiated performers across the subsequent stance phase. The sprinter group in this study generated 50% (at 8.0 m·s^{-1}) and 99% (at 8.5 m·s^{-1}) higher average horizontal external power across the touchdown-velocity-matched stance phases. This was achieved by producing both higher propulsive (between 15 and 19%) and lower braking (between 17 and 21%) impulses across similar contact durations. Sprinters were able to generate higher ground reaction forces compared to the soccer players from late braking phase, through mid-stance and across the majority of the propulsive phase (e.g. resultant force was higher from 21-26%, 33-83% and 86-100% of stance at 8.5 m·s^{-1}, Figure 3). Additionally, sprinters exhibited a more horizontally-orientated force vector during the late braking phase and early propulsive phase (30-60% of stance) and during the latter parts of the propulsive phase (95-98% of stance) at 8.5 m·s^{-1}.

The sprinter group attained the matched touchdown velocities at an earlier step than the soccer players and generated higher average horizontal external power across the contact period which followed, demonstrating the greater accelerative capacity of the sprinters compared with the soccer players studied here. The enhanced horizontal power generated by the sprinters across these specific contact periods was a result of higher forces (resultant force and both the anteroposterior and vertical components of force) being applied against the ground across similar contact durations (Table 3). Previously, athletes with superior accelerative capacity have been characterised as those who are able to produce higher forces and orientate the force vector more horizontally.[8] However, the ability to apply high vertical forces is considered to be a crucial determinant of maximum velocity.[9] Thus, collectively it seems that as athletes approach their velocity plateau and the ground reaction force vector inevitably becomes more vertical, the vertical component of force becomes increasingly more performance-differentiating. In fact, the differences in the vertical force waveforms between groups in this study seemed to become more marked as the touchdown velocity increased from 8.00 $m \cdot s^{-1}$ to 8.25 $m \cdot s^{-1}$ and to 8.50 $m \cdot s^{-1}$ (Figures 2, 3 and S1). This also demonstrates the utility of waveform analysis to uncover new findings beyond those of discrete analyses (for example, mean forces calculated across the entire acceleration phase could mask important performance determinants). Nonetheless, even at these higher velocities, the sprinter group in the current study exhibited a higher ratio of forces than the soccer players (from 30-60% and 95-98% of stance at 8.5 $m \cdot s^{-1}$, for example). Whilst this reinforces the importance of directing the force vector horizontally for high accelerative performance,[8] these findings collectively suggest that from ~60-95% of stance the total amount of force produced differentiates performers to a greater extent than the orientation at which it is applied (the ratio of anteroposterior component to resultant force).

These differences in force production between groups can likely be attributed to the differences in strength-power capacities between groups. Potential explanations include the previously observed non-uniform hypertrophy of thigh musculature,[16] which has been suggested to underpin faster sprinting performances. Specifically, higher eccentric force production capabilities and activation of the knee flexors (hamstring muscles) have been associated with better accelerative performance, likely due to an increased ability to perform negative work in the late swing phase.[17] However, it should be noted that this relates to the initial acceleration phase (where athletes are in a more crouched position and muscle contraction is slower) and potentially not to the late acceleration phase as in the current study (characterised by higher velocity contractions and a more upright posture). The well-established differences in fibre composition and contractile properties between faster and slower runners[18] could also be an underlying difference between groups in this study. Indeed, the rapid development of force across short ground contact periods (rather than the maximum amount of force that an individual can produce) has been identified as a limiting factor to running speed,[19] probably attributable to the ability to produce greater forces at high velocity.[20] Moreover, previously it has been reported that as maximal sprinting speed developed across a 6-month training period, measured ankle joint stiffness during the maximal velocity phase also increased.[21] In fact, reactive ankle strength has been suggested to influence performance in the late acceleration phase,[22] where the ability to quickly reverse eccentric braking forces becomes more important.[5,10]

Unequivocally, the athletes who were able to accelerate to a greater extent beyond the relatively high touchdown velocities (8.0 to 8.5 $m \cdot s^{-1}$) were those who generated higher net horizontal impulse, which could be achieved by increasing propulsive impulse and/or decreasing braking impulse. At the 16-m mark when athletes were running at an average velocity of 8.29 $m \cdot s^{-1}$, Hunter, Marshall and McNair[3] found relative propulsive and braking impulses to be 0.35 and -0.10 $m \cdot s^{-1}$, respectively, which are similar to those achieved by the sprinters in the current study (0.33 $m \cdot s^{-1}$ and -0.11 $m \cdot s^{-1}$ at 8.25 $m \cdot s^{-1}$, Table S1). In fact, the soccer players in the current study produced both lower propulsive impulse (0.27 $m \cdot s^{-1}$) and more negative braking impulses (-0.14 $m \cdot s^{-1}$) at 8.25 $m \cdot s^{-1}$ than athletes in the previous study by Hunter, Marshall and McNair[3]. Morin, Slawinski, Dorel, et al.[7] demonstrated that the higher average net horizontal impulses associated with overall superior accelerative capacity are predominantly determined by higher propulsive, and not lower braking, impulses. However, in the current study, both higher propulsive impulses and lower braking impulses were generated across each of the three ground contacts (matched for touchdown velocity) by the sprinter group compared with the soccer player group (Tables 2 and S1). This discrepancy could be related to the fact that kinetic variables were averaged across the entire acceleration phase in the aforementioned study and impulses were not considered across individual steps. Alternatively, it is plausible that there could be technique-based differences between soccer players and the sprinters analysed in the current and previous studies, or potential differences in the homogeneity of the populations in each study. However, considering the high velocity of these ground contacts (relative to maximum), these findings do seem to align well with other previous research,[5,10] which has shown the attenuation of braking impulses to become progressively more important as the acceleration phase progresses.

The SPM analysis in the current study allowed the identification of specific phases of the (touchdown-velocity-matched) stance where force production differed between the two athlete groups. This analysis illustrated that the anteroposterior component of ground reaction force was predominantly different across the propulsive phase with some differences also observed in the latter part of the braking phase. Specifically, for the initial ~20% of stance, there were no differences in force production across groups. Indeed, previous step-by-step waveform analysis revealed no significant associations between the initial braking forces and performance in sprinters.[10] While elastic storage and return of energy through a stretch-shortening cycle is likely important for propulsion,[23] the amount of impact force at touchdown may be somewhat predetermined by incoming (touchdown) velocity and momentum. Athletes may not have total active control over this early phase of stance, although they do pre-activate their muscles in preparation for touchdown.[24] This theory is somewhat supported by research investigating the joint moments during maximum velocity sprinting, which found hip and ankle joint moments to be small during the initial stance and to peak after ~20% of stance.[4] Thus, the ability to continue acceleration from a given touchdown velocity may be determined to a greater extent by muscle action in the late braking phase and across the propulsive phase.

For each of the touchdown-velocity-matched stance phases studied here, ground contact durations were similar across groups, ranging from 0.105 to 0.111 s in line with previous findings at similar velocities.[9,19] In fact, a strong correlation between maximum velocity and the ground contact time at that maximum velocity has previously been documented.[9] Thus, the limits to the maximum velocity of the slower individuals seem to be more likely attributable to an inability to generate the vertical impulse necessary to produce adequate flight times to continue acceleration, as described previously during treadmill running.[9,19] Interestingly, flight times of the previous step (immediately prior to the velocity-matched touchdown) were longer (7.6-9.8%) for the sprinter group compared with the soccer players. The influence of air resistance on horizontal velocity of individuals with reasonably similar body shape can be considered negligible across short time frames even when the sprinters' flight phases were slightly longer (up to 10 ms). Consequently, the horizontal velocity at the take-off of the previous ground contact will also match across the groups in the current study. Thus, it can be assumed that the between-group difference in the flight time of the previous step is attributable to the sprinters having higher vertical take-off velocity than the soccer players. Weyand, Sternlight, Bellizzi, et al.[9] demonstrated that more rapid repositioning of the swing limbs contributes little to the faster top speeds of better sprinters, and suggested that this process is largely passive through the recoil of elastic structures. Thus, the increased vertical force production during the previous step is likely an important mechanism by which to further increase running speed, by allowing the sprinters sufficient time to configure their lower limbs potentially more favourably for force production across the subsequent stance.

It is, however, not beneficial for sprinters to displace their centre of mass vertically *per se*, as this opposes the main objective of sprinting (to move horizontally as fast as possible) and excessive vertical force production could reduce step frequency. However, clearly a certain amount of vertical force must be produced to increase step length when attaining higher velocities. This highlights an important challenge to balance the different aspects of force production during sprinting. When running at the same velocity (at touchdown) and having similar contact durations (as in the ground contacts analysed in the current study), a velocity increase can be achieved by either generating higher horizontal net impulse or by doing this in combination with higher vertical impulse (if flight times do not become excessively long and result in a step frequency reduction outweighing the increase in step length). Based on our results, it seems that the sprinters were able to achieve a balance between increases in net horizontal and vertical impulses to produce longer step lengths, without disproportionately sacrificing step frequency with overly long flight times, allowing them to continue accelerating.

Across all contact phases studied here, the sprinters force production was significantly higher in the final 10% of stance compared with the soccer players (Figures 2, 3 and S1). However, whether the magnitudes of the differences for the vertical component are practically meaningful could certainly be questioned, as the absolute differences were small (for example 0.42 $N \cdot kg^{-1}$ on average from 90-100% of stance at 8.0 $m \cdot s^{-1}$, equating to ~1.5% of the peak vertical force), but became statistically significant as the variation around the mean was minimal. Some form of magnitude-based analyses across continuous waveforms would complement the SPM analysis in these cases. However, currently no such methods exist to the authors' knowledge. Nonetheless, for the anteroposterior component of force, the differences between groups in the final parts of stance seem to be of greater magnitude (for example 1.09 $N \cdot kg^{-1}$ on average from 90-100% of stance at 8.0 $m \cdot s^{-1}$, equating to ~10% of the peak anteroposterior force component) and thus, could be more noteworthy. There could be two potential explanations for this. Firstly, previous studies of the propulsive phase in maximal velocity running found positive power to be produced by the ankle, whereas the knee produced minimal power and the hip joint exhibited negative power.[4] This transmission of power from the leg to the track during the final part of the propulsion phase has been linked to higher step velocity at an intra-athlete level[25] and thus, may also differentiate performances between the athlete groups in the current study. Secondly, the fact that the soccer players did not wear spikes during the trials could influence their force production in this latter phase of stance. However, whether the magnitude of this potential effect is meaningful is not currently known and the influence of footwear on sprint performance certainly warrants further investigation.

Whilst this study provides new information to better understand the fundamental kinetic differences between athletes of different sprint ability levels, it is conceivable that there could also be between-group kinematic differences, which are not being captured in this study. Future studies should combine kinematics with kinetics to better understand the mechanisms behind these differences in sprint performance. Specifically, we believe that investigations into the influence of flight phase kinematics on joint kinetics during the subsequent contact phase are warranted. Additionally, as only touchdown velocities of 8.0-8.5 $m \cdot s^{-1}$ could be analysed in the current study, it would be interesting for further work to investigate the kinetic factors which allow individuals to accelerate beyond 8.5 $m \cdot s^{-1}$.

Perspectives

This novel study has presented the force production characteristics that allow better sprinters to accelerate beyond the velocities at which others plateau (soccer players in this case). From the same touchdown velocity, sprinters were able to generate higher ground reaction forces compared to the soccer players yet ground contact durations were similar across groups. Force waveforms did not differ across ability levels in the initial braking phase (0-~20% of stance). However, sprinters attenuated the eccentric forces to a greater extent than the soccer players in the late braking phase and produced a higher anteroposterior component of force across almost the entire propulsive phase. Consequently, higher average horizontal power was produced by the sprinters, allowing acceleration to continue beyond the velocity plateau of the soccer players. In order to increase the velocity at which an athlete plateaus, athletes should aim to increase both overall force production and force orientation (higher ratio of forces during the late braking and early propulsive phases) capabilities. Training (including strength training) should be prescribed to increase their ability to produce sufficient vertical force, to withstand and reverse eccentric braking forces and to generate high anteroposterior propulsive force.

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References

1. Haugen TA, Tønnessen E, Hisdal J, Seiler S. The role and development of sprinting speed in soccer. Int J Sports Physiol Perform 2014;9:432-441.
2. Faude O, Koch T, Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. J Sports Sci 2012;30:625-631.
3. Hunter JP, Marshall RN, McNair P. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. J Appl Biomech 2005;21:31-43.
4. Bezodis IN, Kerwin DG, Salo AIT. Lower-limb mechanics during the support phase of maximum-velocity sprint running. Med Sci Sports Exerc 2008;40:707-715.
5. Nagahara R, Mizutani M, Matsuo A, Kanehisa H, Fukunaga T. Association of sprint performance with ground reaction forces during acceleration and maximal speed phases in a single sprint. J Appl Biomech 2017; doi: 10.1123/jab.2016-0356.
6. Mero A, Komi PV. Force-velocity, EMG-velocity, and elasticity-velocity relationships at submaximal, maximal and supramaximal running speeds in sprinters. Eur J Appl Physiol Occup Physiol 1986;55:553-561.
7. Morin JB, Slawinski J, Dorel S, et al. Acceleration capability in elite sprinters and ground impulse: Push more, brake less? J Biomech 2015;48:3149-3154.
8. Rabita G, Dorel S, Slawinski J, et al. Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. Scand J Med Sci Sports 2015;25:583-594.
9. Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. J Appl Physiol 2000;89:1991-1999.
10. Colyer SL, Nagahara R, Salo AIT. Kinetic demands of sprinting shift across the acceleration phase: novel analysis of entire force waveforms. Scand J Med Sci Sports 2018;28:1784-1792.
11. Volkov NI, Lapin VI. Analysis of the velocity curve in sprint running. Med Sci Sports Exerc 1979;11:332-337.
12. Salo A, Bezodis I. Which starting style is faster in sprint running - standing or crouch start? Sports Biomechanics 2004;3:43-53.
13. Bezodis NE, Salo AIT, Trewartha G. Choice of sprint start performance measure affects the performance-based ranking within a group of sprinters: Which is the most appropriate measure? Sports Biomechanics 2010;9:258-269.
14. Hopkins WG, Marshall SW, Batterham A, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc 2009;41:3-12.
15. Pataky TC. One-dimensional statistical parametric mapping in Python. Computer Methods in Biomechanics and Biomedical Engineering 2012;15:295-301.
16. Handsfield GG, Knaus KR, Fiorentino NM, Meyer CH, Hart JM, Blemker SS. Adding muscle where you need it: non-uniform hypertrophy patterns in elite sprinters. Scand J Med Sci Sports 2017;27:1050-1060.
17. Nagahara R, Matsubayashi T, Matsuo A, Zushi K. Alteration of swing leg work and power during human accelerated sprinting. Biology Open 2017;6:633-641.
18. Costill DL, Daniels J, Evans W, Fink W, Krahenbuhl G, Saltin B. Skeletal-muscle enzymes and fiber composition in male and female track athletes. J Appl Physiol 1976;40:149-154.
19. Weyand PG, Sandell RF, Prime DN, Bundle MW. The biological limits to running speed are imposed from the ground up. J Appl Physiol 2010;108:950-961.
20. Morin JB, Bourdin M, Edouard P, Peyrot N, Samozino P, Lacour JR. Mechanical determinants of 100-m sprint running performance. Eur J Appl Physiol 2012;112:3921-3930.
21. Nagahara R, Zushi K. Development of maximal speed sprinting performance with changes in vertical, leg and joint stiffness. Journal of Sports Medicine and Physical Fitness 2017;57:1572-1578.

22. Nagahara R, Naito H, Miyashiro K, Morin JB, Zushi K. Traditional and ankle-specific vertical jumps as strength-power indicators for maximal sprint acceleration. Journal of Sports Medicine and Physical Fitness 2014;54:691-699.
23. Putnam CA, Kozey JW. Substantive issues in running. In: Vaughan CL ed, Biomechanics of Sport. Boca Raton, FL: CRC Press; 1989:1-33.
24. Mero A, Komi PV. Electromyographic activity in sprinting at speeds ranging from sub-maximal to supra-maximal. Med Sci Sports Exerc 1987;19:266-274.
25. Bezodis I, Salo AIT, Kerwin D. Joint kinetics in maximum velocity sprint running. In: Proceedings of the 25th International Symposium on Biomechanics in Sports; 2007; Ouro Preto, Brazil.

Figure Captions

Figure 1. Mean step-averaged velocities of the sprint specialists (red) and soccer players (black). Shading represents standard deviations.

Figure 2. Normalised mean ground reaction force curves produced by sprinters (black) and soccer players (red) across ground contact periods with touchdown velocity of 8.0 $m \cdot s^{-1}$ and the associated SPM-1D *t*-test result for differences between the curves. From left to right: resultant force, anteroposterior component of the ground reaction force, vertical component of the ground reaction force and ratio of forces (anteroposterior component to resultant force). Grey shaded areas indicate supra-threshold clusters, which are indicative of statistically significant differences between curves at those specific nodes (% of stance).

Figure 3. Normalised mean ground reaction force curves produced by sprinters (black) and soccer players (red) across ground contact periods with touchdown velocity of 8.5 $m \cdot s^{-1}$ and the associated SPM-1D *t*-test result for differences between the curves. From left to right: resultant force, anteroposterior component of the ground reaction force, vertical component of the ground reaction force and ratio of forces (anteroposterior component to resultant force). Grey shaded areas indicate supra-threshold clusters, which are indicative of statistically significant differences between curves at those specific nodes (% of stance).

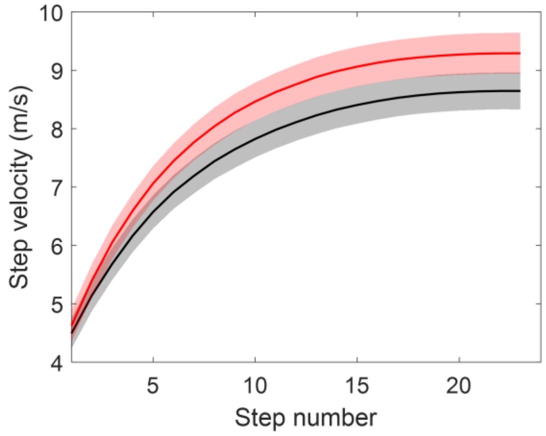

Figure 1.

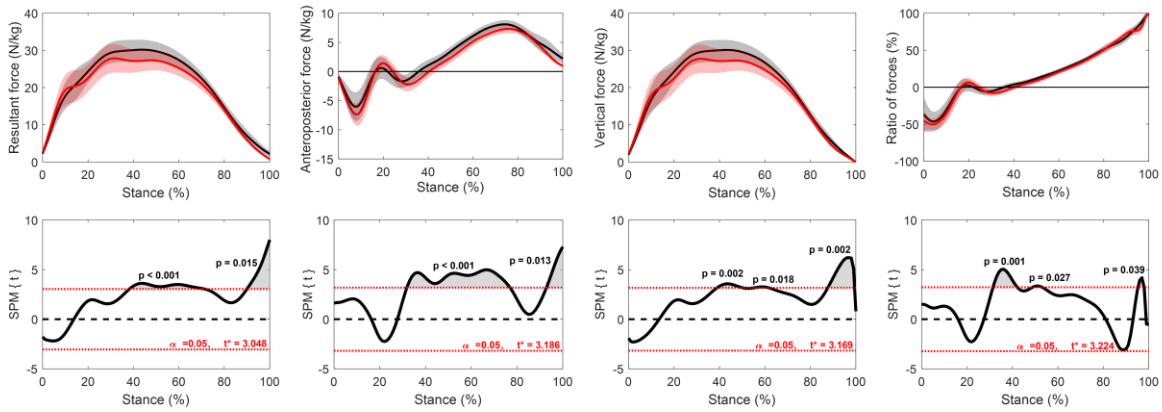

Figure 2.

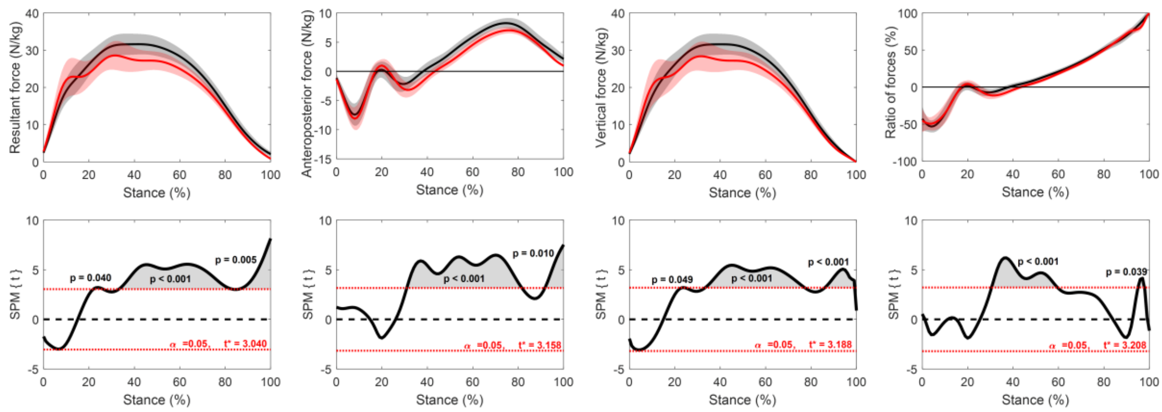

Figure 3.

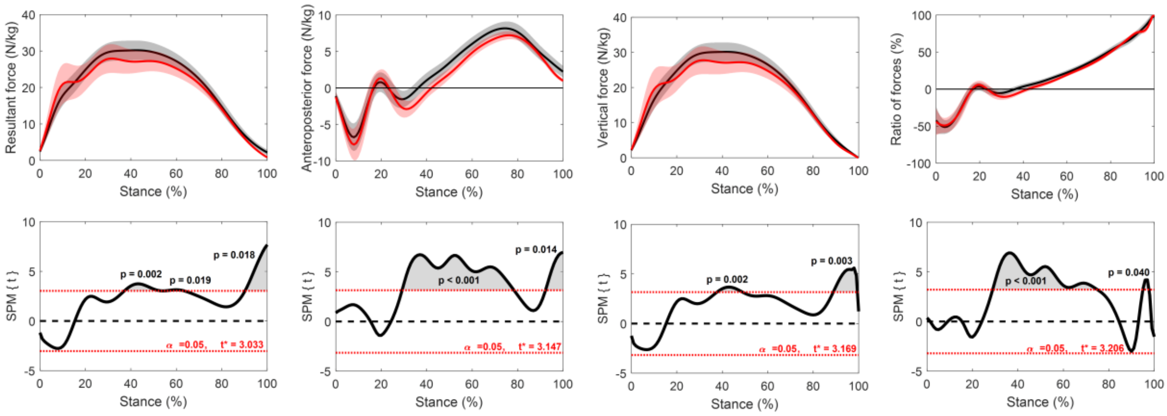

Figure S1. Normalised mean ground reaction force curves produced by sprinters (black) and soccer players (red) across ground contact periods with touchdown velocity of 8.25 $m \cdot s^{-1}$ and the associated SPM-1D t-test result for differences between the curves. From left to right: resultant force, anteroposterior component of the ground reaction force, vertical component of the ground reaction force and ratio of forces (anteroposterior component to resultant force). Grey shaded areas indicate supra-threshold clusters, which are indicative of statistically significant differences between curves at those specific nodes (% of stance).

Table 1. Horizontal velocities at touchdown, step number and distance of step (mean ± SD) for touchdown velocity-matched (8.00, 8.25 and 8.50 $m \cdot s^{-1}$) steps

	8.00 $m \cdot s^{-1}$		8.25 $m \cdot s^{-1}$		8.50 $m \cdot s^{-1}$	
	Sprinters	Soccer players	Sprinters	Soccer players	Sprinters	Soccer players
Number of athletes	24	24	27	22	28	21
Step number	9.8 ± 2.3	12.8 ± 3.1	10.3 ± 1.6	14.1 ± 3.1	11.6 ± 2.2	17.4 ± 5.2
Distance of step (m)	11.3 ± 2.1	15.9 ± 3.9	13.0 ± 2.6	18.9 ± 3.7	14.7 ± 3.4	23.9 ± 6.3
Horizontal touchdown velocity ($m \cdot s^{-1}$)	8.00 ± 0.08	8.01 ± 0.05	8.25 ± 0.07	8.25 ± 0.04	8.50 ± 0.06	8.50 ± 0.03

Table 2. Absolute and relative braking, propulsive and net horizontal impulses (mean ± SD) produced by sprinters and soccer players across ground contacts with matched touchdown velocities (8.0 and 8.5 m/s) and effect sizes (± 90% CI) representing between-group differences.

		8.0 m/s		8.5 m/s	
		Sprinters	Soccer players	Sprinters	Soccer players
Absolute impulse (N·s)	Net horizontal	**15.9 ± 4.5**	11.2 ± 4.4	**12.5 ± 4.3**	7.6 ± 2.5
	Effect size ± 90% CI	0.94 ± 0.41		1.11 ± 0.40	
	Propulsive	**22.7 ± 3.3**	19.8 ± 3.1	**20.9 ± 3.1**	17.6 ± 2.4
	Effect size ± 90% CI	0.82 ± 0.43		1.02 ± 0.42	
	Braking	**-6.8 ± 2.7**	-8.6 ± 2.3	**-8.3 ± 2.5**	-10.0 ± 1.7
	Effect size ± 90% CI	0.72 ± 0.45		0.69 ± 0.47	
Relative impulse (m/s)	Net horizontal	**0.24 ± 0.07**	0.16 ± 0.06	**0.19 ± 0.07**	0.11 ± 0.03
	Effect size ± 90% CI	1.05 ± 0.39		1.18 ± 0.39	
	Propulsive	**0.34 ± 0.04**	0.29 ± 0.04	**0.31 ± 0.04**	0.25 ± 0.03
	Effect size ± 90% CI	1.10 ± 0.38		1.25 ± 0.37	
	Braking	**-0.10 ± 0.04**	-0.13 ± 0.03	**-0.13 ± 0.03**	-0.14 ± 0.02
	Effect size ± 90% CI	0.64 ± 0.46		0.59 ± 0.49	

Bold denotes substantially higher value (more positive or less negative) for sprinters compared to soccer players. CI = confidence intervals

Table 3. Discrete variables relating to the ground contact following (or flight phase prior to) the velocity-matched touchdowns (8.0 and 8.5 m/s) for the sprinters and soccer players, and effect sizes (± 90% CI) representing between-group differences.

	8.0 m/s		8.5 m/s	
	Sprinters	Soccer players	Sprinters	Soccer players
Average horizontal external power (W/kg)	**17.9 ± 4.8**	11.9 ± 2.6	**15.7 ± 5.2**	7.9 ± 3.4
Effect size ± 90% CI	0.91 ± 0.31		1.29 ± 0.32	
Mean resultant force (N/kg)	**20.5 ± 1.7**	19.2 ± 1.2	**21.4 ± 1.2**	19.6 ± 1.5
Effect size ± 90% CI	0.58 ± 0.30		0.88 ± 0.21	
Mean anteroposterior force (N/kg)	**2.5 ± 0.6**	1.7 ± 0.5	**2.4 ± 0.5**	1.5 ± 0.6
Effect size ± 90% CI	0.88 ± 0.28		1.22 ± 0.33	
Mean vertical force (N/kg)	**19.6 ± 1.2**	18.4 ± 1.6	**19.6 ± 1.2**	18.6 ± 1.8
Effect size ± 90% CI	0.53 ± 0.20		0.41 ± 0.30	
Mean ratio of forces (%)	**18.4 ± 2.6**	16.8 ± 2.6	**16.8 ± 2.3**	15.3 ± 2.0
Effect size ± 90% CI	0.41 ± 0.32		0.48 ± 0.33	
Ground contact duration (s)	0.109 ± 0.006	0.111 ± 0.007	0.105 ± 0.006	0.107 ± 0.007
Effect size ± 90% CI	0.28 ± 0.49		0.30 ± 0.45	
Previous step flight time (s)	**0.109 ± 0.012**	0.101 ± 0.011	**0.113 ± 0.012**	0.105 ± 0.010
Effect size ± 90% CI	0.69 ± 0.45		0.72 ± 0.45	

Bold denotes substantially higher value for sprinters compared to soccer players. CI = confidence intervals

Table S1. Absolute and relative braking, propulsive and net horizontal impulses produced by sprinters and soccer players and the discrete kinetic variables (mean ± SD) relating to the ground contact following (or flight phase prior to) the 8.25 m/s velocity-matched touchdown. Effect sizes (± 90% CI) represent between-group standardised differences.

		8.25 m/s	
		Sprinters	Soccer players
Absolute impulse (N·s)	Net horizontal	**14.9 ± 4.2**	9.8 ± 4.4
	Effect size ± 90% CI	1.03 ± 0.38	
	Propulsive	**21.9 ± 3.2**	18.6 ± 2.5
	Effect size ± 90% CI	1.00 ± 0.38	
	Braking	**-7.0 ± 2.3**	-8.8 ± 2.6
	Effect size ± 90% CI	0.94 ± 0.41	
Relative impulse (m/s)	Net horizontal	**0.23 ± 0.06**	0.13 ± 0.05
	Effect size ± 90% CI	1.26 ± 0.34	
	Propulsive	**0.33 ± 0.05**	0.27 ± 0.03
	Effect size ± 90% CI	1.20 ± 0.36	
	Braking	**-0.11 ± 0.03**	-0.14 ± 0.04
	Effect size ± 90% CI	0.87 ± 0.42	
Average horizontal external power (W/kg)		**17.9 ± 4.9**	10.0 ± 3.9
	Effect size ± 90% CI	1.25 ± 0.30	
Mean anteroposterior force (N/kg)		**2.4 ± 0.5**	1.5 ± 0.6
	Effect size ± 90% CI	1.22 ± 0.33	
Mean vertical force (N/kg)		**19.6 ± 1.2**	18.6 ± 1.8
	Effect size ± 90% CI	0.41 ± 0.30	
Mean resultant force (N/kg)		**20.5 ± 1.3**	19.4 ± 1.8
	Effect size ± 90% CI	0.46 ± 0.30	
Mean ratio of forces (%)		**18.2 ± 2.5**	16.1 ± 2.1
	Effect size ± 90% CI	0.64 ± 0.32	
Ground contact duration (s)		0.108 ± 0.006	0.110 ± 0.007
	Effect size ± 90% CI	0.26 ± 0.25	
Previous step flight time (s)		**0.112 ± 0.011**	0.102 ± 0.009
	Effect size ± 90% CI	0.91 ± 0.42	

Bold denotes substantially higher value (more positive or less negative) for sprinters compared to soccer players. CI = confidence intervals